

BSM Higgs boson searches at LHC and the Tevatron

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ABSTRACT

A review of the current experimental results on searches for Higgs bosons in models beyond the Standard Model is presented. Searches from ATLAS, CMS and LHCb use datasets from Run 1 of the LHC, including 7 and 8 TeV proton-proton collisions. Searches from CDF and D0 use the full or partial 1.96 TeV proton-anti-proton collision datasets from the Tevatron.

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The discovery of a Higgs boson [1, 2] by the ATLAS [3] and CMS [4] experiments at the Large Hadron Collider (LHC) [5] has shed light on the mechanism for electroweak symmetry breaking. However, it still remains to be determined whether the particle is indeed the predicted Higgs boson of the Standard Model (SM), or whether it is something different — a Higgs boson from Beyond the Standard Model (BSM). The consistency of the particle with the SM Higgs boson has been demonstrated through its property measurements, which can also be used to place indirect limits on BSM Higgs bosons [6, 7]. However, many models with extended or modified Higgs sectors are also consistent with these measurements, and the possibility of multiple Higgs bosons still remains.

An alternate route to uncover the nature of the Higgs sector is via direct searches. This talk provides a review of searches for BSM Higgs bosons conducted at the LHC and the Tevatron, including: neutral and charged scalars within Two-Higgs-Doublet-Models (2HDMs), the Minimal Supersymmetric Standard Model (MSSM) and the Next-To-Minimal Supersymmetric Standard Model (NMSSM); doubly-charged scalars; cascade decays; exotic decays to invisible or long-lived particles; and Fermiophobic models.

One of the simplest extensions to the Standard Model Higgs sector is an inclusion of an additional Higgs doublet, resulting in a broad class of models known as 2HDMs. These models have a rich phenomenology, with five physical Higgs bosons remaining after spontaneous symmetry breaking: two neutral CP -even (h and H), one neutral CP -odd (A) and two charged bosons (H^\pm). The MSSM is a particular case of a 2HDM in which the whole Higgs sector can be described at tree-level by just two additional parameters, typically chosen to be the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, and either the mass of the A or H^\pm bosons, m_A or m_{H^\pm} , respectively. Couplings of the Higgs bosons to τ -leptons and b -quarks can be significantly enhanced, especially for large values of $\tan\beta$, making searches in the $\tau\tau$ and $b\bar{b}$ modes the most sensitive to neutral MSSM bosons. The searches also typically take advantage of the strongly enhanced b -quark associated production mechanism via the use of b -tagging.

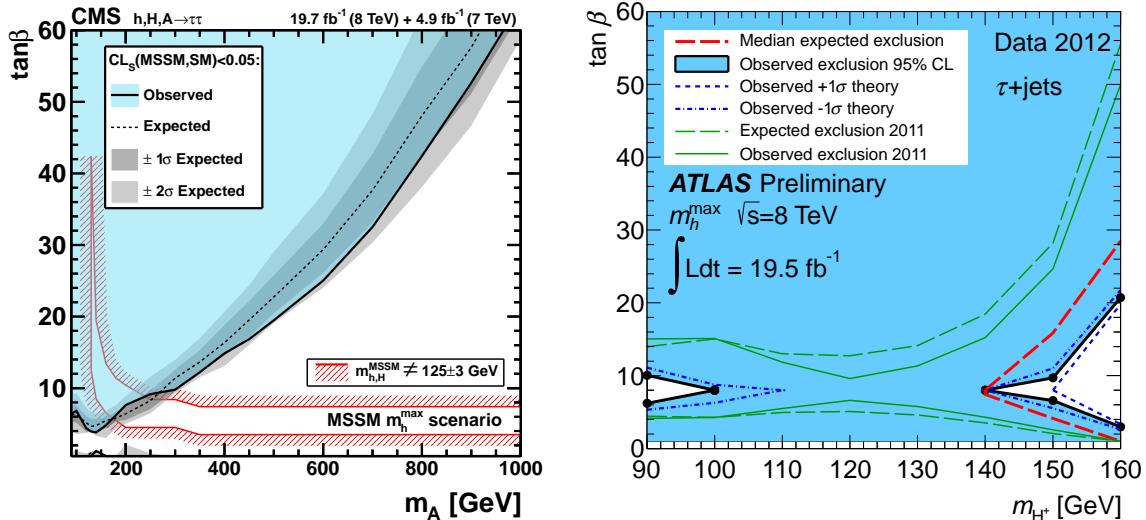


Figure 1: Left: Limit in the MSSM parameter space from a search for $h/H/A \rightarrow \tau\tau$ by CMS [9]. Right: Limit in the MSSM parameter space from a search for $H \rightarrow \tau\nu$ by ATLAS [15].

Searches for neutral Higgs bosons decaying to τ -lepton pairs have been performed by ATLAS [8], CMS [9], LHCb [10], CDF [11] and D0 [12]. The most stringent limits come from CMS, where the full 7 and 8 TeV datasets from the LHC are used. The search analyses all possible $\tau\tau$ decay modes except the mode where both τ -leptons decay to $e\nu\nu$, which suffers large backgrounds and has a small branching fraction. Events containing well identified decay products of two oppositely charged τ -leptons are selected. Further selection based on the kinematic properties of the τ decays is used to suppress W/Z +jets events. Finally, the events are categorised by the presence or absence of at least one b -tagged jet. An excess of events over the SM background is searched for in the reconstructed $\tau\tau$ mass distribution. The dominant backgrounds come from

$Z/\gamma^* \rightarrow \tau\tau$ production and from W +jets and multijet production where one or two jets, respectively, are misidentified as electrons, muons or hadronic τ decays. The search excludes large portions of the parameter space for m_A in the range 90 – 1000 GeV, as seen in Figure 1 (left). Searches for neutral MSSM Higgs bosons in the $b\bar{b}$ channel have also been performed by CDF and D0 [13], and by CMS [14]. However, these searches are not as sensitive due to the large background from irreducible $b\bar{b}$ production.

Searches for charged Higgs bosons at the LHC and Tevatron have thus far primarily targeted H^\pm with a mass lower than the top-quark mass. In this case, the dominant production is in $t\bar{t}$ decays, where one top-quark decays via a charged Higgs boson and the other via a W boson. For $\tan\beta \gtrsim 3$, the charged Higgs boson decays predominantly via $H^\pm \rightarrow \tau\nu$, while for $\tan\beta < 3$, the $H \rightarrow c\bar{s}$ decay can be significant. Searches are typically divided based on whether the W -boson and τ -lepton decay hadronically or leptonically. Searches have been performed by ATLAS [15, 16, 17], CMS [18] and CDF [19], covering the τ +jets, τ +lepton and $c\bar{s}$ +lepton final states. The strongest limits come from the τ +jets channel at ATLAS, which uses the full 8 TeV dataset from the LHC. Events containing exactly one identified τ candidate, at least four additional jets (at least one b -tagged), no leptons and large missing transverse momentum are selected. An excess over the dominant background from SM $t\bar{t}$ production is searched for in the distribution of the transverse-mass between the missing transverse momentum and the τ candidate. The search excludes almost the entire available parameter space for $90 < m_{H^\pm} < 160$ GeV, as shown in Figure 1 (right). The search also places limits for $m_{H^\pm} > m_t$, although the sensitivity is significantly reduced due to the dominant $H^\pm \rightarrow t\bar{b}$ decay mode.

2HDMs open up the possibility for a variety of *cascade decays* involving multiple Higgs bosons. Searches for such decays have been performed by ATLAS [20] and CDF [21] in the $H \rightarrow W^- H^+ (\rightarrow W^+ h)$ channel, and CMS [22] in the $H \rightarrow 2h$ and $A \rightarrow Zh$ channels. The signatures typically involve some combination of multi-leptons, b -jets and photons. The searches are able to exclude some regions of the 2HDM parameter space, as shown in Figure 2 (left) for Type-I 2HDMs [23]. Recently ATLAS has also published a search for resonant and non-resonant production of two Higgs bosons in the $X \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ mode [24]. The corresponding limit for resonant production is shown in Figure 2 (right). Cascade decays of Supersymmetric particles involving Higgs bosons are also possible [25], but are not reviewed here.

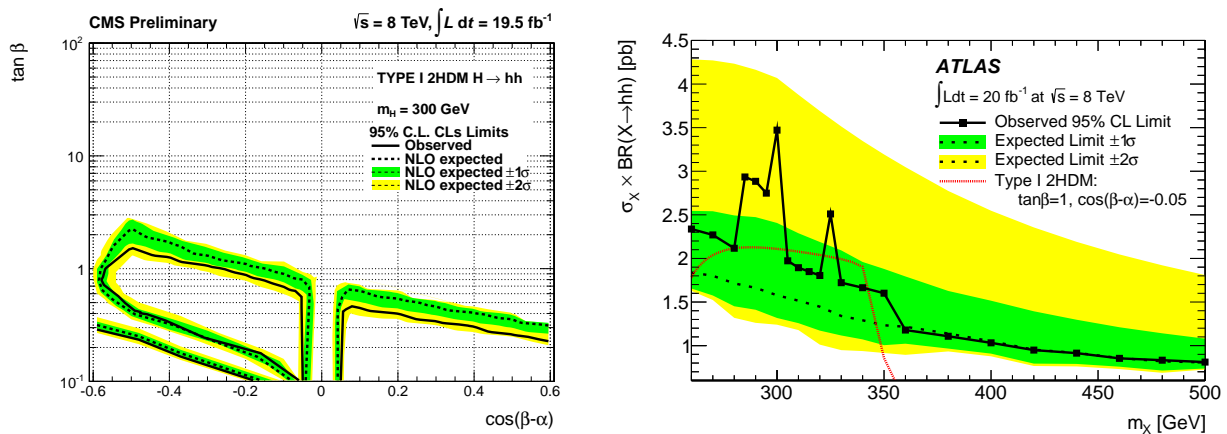


Figure 2: Left: Limits on Type-I 2HDMs from a search for $H \rightarrow hh$ by CMS [22], where α is the h - H mixing angle and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. Right: Limits on resonant $X \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ production from ATLAS [24].

2HDMs can also exhibit large enhancements to processes involving flavour changing neutral currents. In particular, the $t \rightarrow Hc$ branching fraction, which is predicted to be $3 \cdot 10^{-15}$ in the SM can be as large as $1.5 \cdot 10^{-3}$ in some 2HDM models [26]. Searches for the flavour changing neutral current process $t \rightarrow Hc$ in $t\bar{t}$ events have been performed by ATLAS [27] and CMS [28]. In the search from ATLAS, the $H \rightarrow \gamma\gamma$ decay is specifically targeted and a full reconstruction of the $t\bar{t}$ system is performed, while the CMS result is a reinterpretation of multilepton plus photon searches, which also covers $H \rightarrow WW$ and $H \rightarrow ZZ$ modes.

The searches put upper limits on $\mathcal{B}(t \rightarrow Hc)$ of 0.83% and 0.56%, respectively. The limit from ATLAS is shown in Figure 3 (left).

In the NMSSM, a Higgs singlet is added to the MSSM Higgs sector. This results in seven physical Higgs bosons: five neutral and two charged. In the most general case, the neutral Higgs bosons can have mixed CP states, allowing for CP violation in the Higgs sector. The lightest Higgs boson can be very light (less than one GeV), in which case decays to $b\bar{b}$ are not kinematically possible, which significantly alters the branching fractions. Due to helicity suppression, the branching fraction to the heaviest possible pair of particles is significantly enhanced. Decays into $\mu\mu$ are dominant just above the dimuon production threshold, low-multiplicity states of light hadrons become dominant above the 3π threshold, followed by $\tau\tau$ and then $b\bar{b}$. Below the dimuon threshold, the $\gamma\gamma$ mode can be sensitive. Searches for a light neutral Higgs boson of the NMSSM have been performed by ATLAS in the $a \rightarrow \mu\mu$ [29] and $h \rightarrow 2a \rightarrow 4\gamma$ [30] channels, by CMS in the $a \rightarrow 2\mu$ [31] and $h \rightarrow 2a \rightarrow 4\mu$ [32] channels, and by D0 in the $h \rightarrow 2a \rightarrow 4\mu$ and $h \rightarrow 2a \rightarrow 2\mu 2\tau$ channels [33]. The limit from the CMS search for $h \rightarrow 2a \rightarrow 4\mu$ is shown in Figure 3 (right). The search is conducted by counting events that contain two well reconstructed muon pairs with a good mass compatibility. The dominant backgrounds are from B -meson and J/ψ pair-production. The search places strong limits for a light Higgs boson in the mass range from $2m_\mu$ to $2m_\tau$. The NMSSM also opens up the possibility for decays of a charged Higgs boson via a light neutral Higgs boson. CDF has performed a search for such a decay from a parent top-quark: $t \rightarrow H^+b \rightarrow Wa(\rightarrow \tau\tau)b$ [34]. They can place limits as strong as $\mathcal{B}(t \rightarrow H^+b) < 10\%$ for some regions of parameter space.

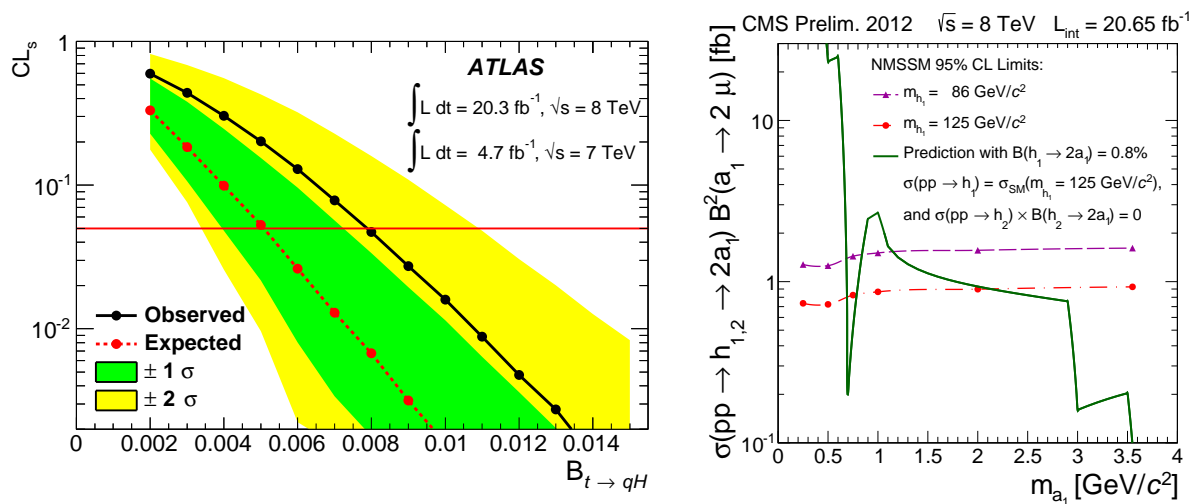


Figure 3: Left: Limits on the flavour changing $t \rightarrow qH$ ($q = u, c$) process from ATLAS [27]. Right: Limits on the lightest neutral Higgs boson of the NMSSM from a search for $h \rightarrow 2a \rightarrow 4\mu$ by CMS [32].

Following the observation of non-zero neutrino masses through neutrino oscillations, several mechanisms for neutrino mass generation have been proposed, of which the see-saw mechanism is one of the most compelling. In the minimal type-II neutrino see-saw model, a scalar triplet is introduced, which contains doubly charged Higgs bosons. Observation of such particles would establish the type-II seesaw model as the most promising mechanism for neutrino mass generation. At the LHC and Tevatron, searches for doubly charged Higgs bosons have been performed by ATLAS [35], CMS [36] and D0 [37]. The searches typically require at least three reconstructed leptons (including hadronic τ decays) and look for an excess of events over the SM background in the mass distribution of same-sign lepton pairs. The searches put limits on the doubly charged Higgs boson mass of around 400 GeV, depending on the assumed branching fractions, as shown in Figure 4.

While coupling measurements provide constraints on the decay modes of the discovered Higgs boson, the possibility of a non-negligible branching fraction into exotic particles remains. Invisible decays of the Higgs boson are possible in a wide range of models (e.g. neutralinos, graviscalars, etc.). Searches for invisible

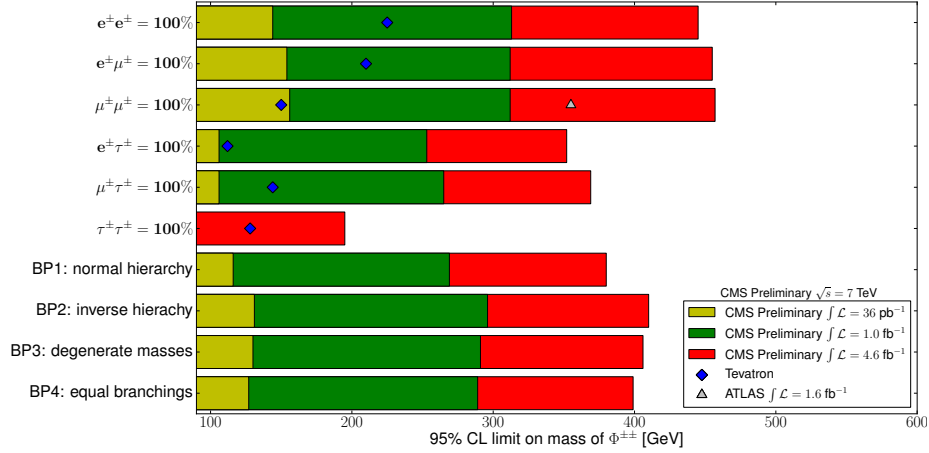


Figure 4: Limits on the mass of doubly charged Higgs bosons from CMS, ATLAS and Tevatron [36].

decays of the Higgs boson have been performed by ATLAS [38], CMS [39] and CDF [40]. The searches rely on production of the Higgs boson in association with a vector boson or via vector boson fusion, in which case the momentum of the recoiling visible-system will lead to a large measured missing transverse momentum. The dominant backgrounds typically involve $Z \rightarrow \nu\nu$ or $W \rightarrow \ell\nu$ decays in production with an additional Z boson or jets. The searches put an upper limit of about 60% at the 95% confidence level on the invisible branching fraction of the discovered Higgs boson. These limits can be used to place limits on *Higgs portal* models, in which the Higgs boson provides an interaction between the SM and the dark-sector, as shown in Figure 5.

Some models, such as Hidden Valley models or Baryon Violating Supersymmetry, predict decays of the Higgs boson to long-lived particles (e.g. ν -hadrons or the lightest Supersymmetric particle). The typical signature is high-multiplicity jets of hadronic particles produced from a displaced vertex. Searches for Higgs bosons decaying into exotic long-lived particles have been performed by LHCb [41], D0 [42] and CDF [43, 44]. The searches rely on the reconstruction of at least 2 high-quality secondary vertices. The large background due to vertices originating from an interaction with the detector material is removed via geometrical selection. The dominant uncertainties typically arise from the efficiency of the trigger and the vertex reconstruction. The searches have most sensitivity when the particles decay far enough from the primary vertex so that they can be distinguished from the hadronic background. However, sensitivity is lost quickly once the particles decay outside the tracking volume. The search from D0 almost has enough sensitivity to exclude the production of a SM-like Higgs boson decaying to a pair of ν -hadrons, depending on the properties of the ν -hadrons.

Extensions of the SM Higgs sector, e.g. 2HDMs or Higgs triplet models, can also predict substantially suppressed couplings to fermions. The most common way to distinguish such models is to search for an enhancement in the $H \rightarrow \gamma\gamma$ branching fraction, while WW and ZZ modes have also been considered. Searches for *fermiophobic* Higgs bosons have been performed by ATLAS [45], CMS [46], CDF and D0 [47]. The CMS search excludes a purely fermiophobic Higgs boson with a mass in the range 110–147 GeV. Slightly weaker limits are placed by the other experiments.

In conclusion, the LHC and Tevatron experiments have developed an extensive range of searches for BSM Higgs bosons. While no significant deviations from the SM have yet been observed, the stage is set for an exciting Run 2 of the LHC.

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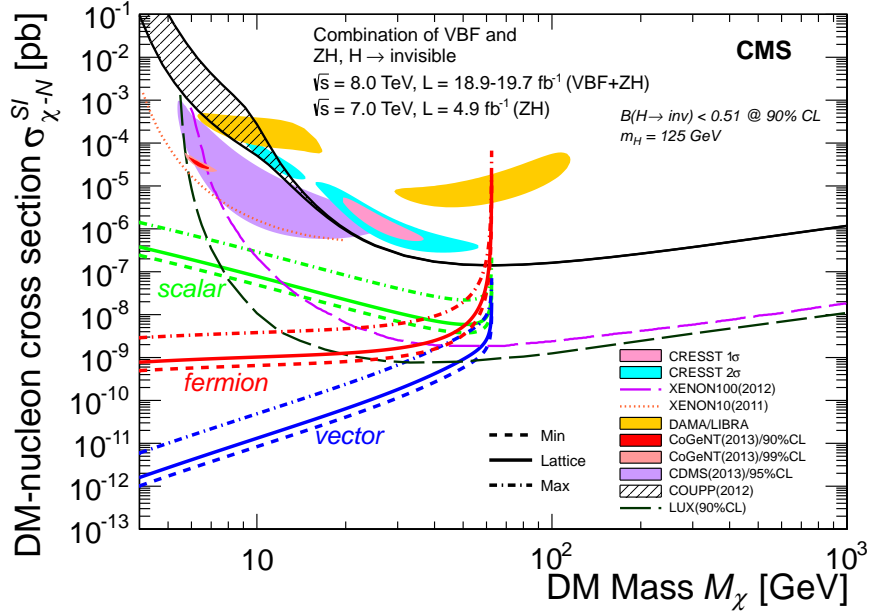


Figure 5: Limits on *Higgs Portal* dark matter models from a combination of direct searches for Higgs decays to invisible particles by CMS [39]. The limits depend on the assumed nature of the dark-matter candidate: *vector*, *fermion* or *scalar*. Indirect limits or preferred regions from direct detection experiments are overlaid.

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